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Systematic and integrated approach to tropical cyclone track forecasting in the eastern and central North Pacific

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SYSTEMATIC AND INTEGRATED APPROACH TO TROPICAL CYCLONE TRACK FORECASTING IN THE EASTERN AND CENTRAL NORTH PACIFIC

by

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December, 1995

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SYSTEMATIC AND INTEGRATED APPROACH TO TROPICAL CYCLONE TRACK FORECASTING IN THE EASTERN AND CENTRAL NORTH PACIFIC

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This study is the application of the meteorological framework in the Systematic Approach to tropical cyclone track forecasting of Carr and Elsberry to the eastern and central North Pacific tropical cyclones. All eastern and central North Pacific tropical cyclones from 1990-1993 are examined using 500 mb Navy Operational Global Atmospheric Prediction System streamline and isotach analyses, geostationary satellite imagery, and the tropical cyclone best-track information. Application of the Systematic Approach to the eastern and central North Pacific requires modifications in the Environment Structure and TC-Environment transitional mechanisms: (i) A Low Synoptic Pattern is defined; and (ii) a Weak Westerly Synoptic Region is defined in the Standard Synoptic Pattern. A four-year climatology of Synoptic Patterns, Regions, Pattern/Regions, and transitions is developed. The Standard Pattern and Dominant Ridge Region are the most common because of the dominance of the subtropical ridge in eastern and central North Pacific tropical cyclone motion. However, two subregions in the subtropical ridge with different tilts account for track direction variations from south of west to north of west within the Standard Synoptic Pattern. Storm tracks in each Pattern/Region combination reveal a characteristic track motion for each Pattern/Region. Subtropical Ridge Modification is found to be the most important transitional mechanism.

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I. INTRODUCTION

A. TROPICAL CYCLONE TRACK FORECASTING

The accurate forecasting of tropical cyclone (TC) movement is important for a large portion of the world. Tropical meteorologists at centers throughout the world are continually striving to reduce their forecast errors of tropical cyclone movement. Major decisions are based on the forecast movement of tropical cyclones. A mistake in the forecast movement of a tropical cyclone can endanger lives, ships, businesses, and homes. The Joint Typhoon Warning Center (JTWC) in Guam is responsible for forecasting tropical cyclones in the western North Pacific. The National Hurricane Center (NHC) in Miami, Florida has the responsibility for the North Atlantic and eastern North Pacific to 140° W while the Central Pacific Hurricane Center is responsible for central North Pacific from 140° W to 180° W.

Many problems exist in the forecasting of tropical cyclones. A large problem is the lack of observations throughout most of the tropical oceans. To combat this, forecasters use objective aids and numerical weather prediction models to help them in their forecasts. The numerical weather prediction models are viewed as the most likely tool to provide an integrated TC track and structure forecast, and thus lead to an advancement in TC forecasting. However, these models have systematic errors in TC track forecasts. The knowledge that forecasters acquire through experience is another invaluable tool. The combination of numerical guidance, objective aids, and experience-gained knowledge is often expressed in terms of thumb-rules. These thumb-rules and their application can vary greatly between warning centers. This variation in application can be even greater between individual forecasters. The temporal consistency of the official forecasts may be degraded, and may not improve upon objective forecasts as expected (Elsberry and Dobos 1990).

Carr and Elsberry (1994; hereafter CE) believe the principal weaknesses in TC forecasting are:

- insufficiently integrated and balanced treatment of the track, intensity, and wind distribution sub-problems;
- an environment-driven perspective that does not sufficiently account for significant interaction of the TC with its environment;
- excessive reliance on empirical techniques and thinking so that dynamical reasoning is underemphasized; and
- an insufficiently systematic and standardized approach, which results in degradation of forecast temporal consistency.

Using these weaknesses as motivation, CE proposed a new systematic and integrated approach to tropical cyclone track forecasting (abbreviated title of Systematic Approach).

The Systematic Approach was developed to help forecasters more insightfully and consistently: (i) interpret the TC motion characteristics based on evolving global numerical model fields; and (ii) anticipate errors in the TC forecast tracks provided by the global model and by other objective track forecast aids that depend on the numerical model (Carr et al. 1995). CE contains an extensive description of the meteorological knowledge base utilized. The Systematic Approach was designed around the procedures and techniques of JTWC in Guam and the analyses and forecasts of the U.S. Navy Fleet Numerical Meteorology and Oceanography Center (FNMOC) in Monterey, CA.

The Systematic Approach to TC track forecasting is organized into three phases: Numerical Guidance Analysis, Objective Techniques Analysis, and Official Forecast Development (Fig. 1). Each of these phases is further divided into resources, knowledge bases, and process components. CE provides details on these specific components.

The remainder of this Chapter reviews the Numerical Guidance Analysis phase. The knowledge base of the Numerical Guidance is the TC-Environment conceptual models proposed by CE. The conceptual models developed in the Systematic Approach characterize the Environment Structure, the TC Structure, and the TC-Environment transitions.

B. ENVIRONMENT STRUCTURE

The Environmental Structure is defined by CE in terms of Synoptic Patterns and Synoptic Regions. The Synoptic Patterns are the large-scale circulation features including adjacent cyclones and anticyclones. CE identify four synoptic Patterns in the western North Pacific basin (Fig. 2). Within each of the four Synoptic Patterns are six Synoptic Regions (Fig. 2) that are associated with a particular environmental steering that is imposed on the TC. The following is a brief explanation of each Synoptic Pattern and Region (see CE for further descriptions).

Systematic Approach Flowchart

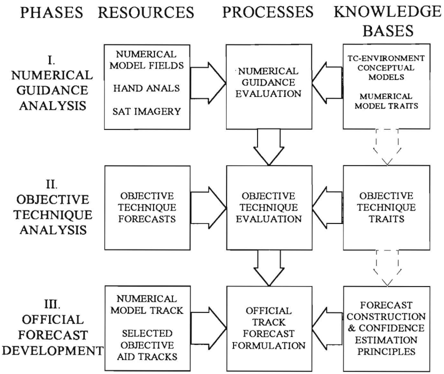


Figure 1. Schematic flow chart of the three phases (left side) and components (top) in the systematic and integrated approach to TC track forecasting (from Carr and Elsberry 1994).

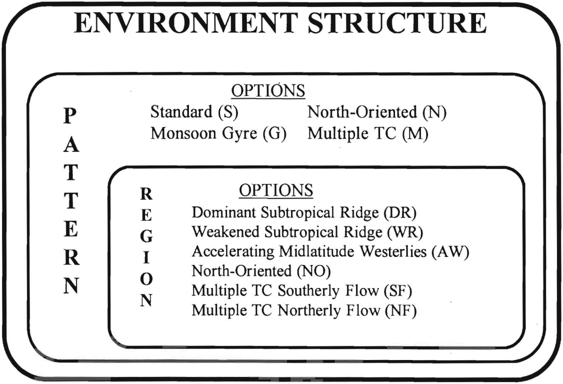


Figure 2. Environmental Structure for the western North Pacific tropical basin comprised of Synoptic Patterns and further subdivided into Synoptic Regions (from Carr et al. 1995).

1. Synoptic Patterns

The Synoptic Patterns are a conceptual model using Navy Operational Global Atmospheric Prediction System (NOGAPS) streamline and isotach analyses primarily at 500 mb. The structure and orientation of the mid-tropospheric subtropical ridge is the prominent feature in many of the conceptual models. The four Synoptic Patterns are Standard (S), North-Oriented (N), Monsoon Gyre (G), and Multiple (M) Tropical Cyclone.

The S Synoptic Pattern is identified when the axis of the ridge circulation influencing the steering of the TC is approximately zonally-oriented. Ideally, the subtropical ridge separates the tradewind easterlies and the mid-latitude westerly flow. The ridge structure may be modulated by mid-latitude troughs.

The conditions for classifying a Synoptic Pattern as N are: (i) a significant break in the subtropical ridge must be present poleward of the TC; and (ii) a prominent, and primarily north-south oriented, ridge to the east of the ridge break that also extends significantly equatorward of the latitude of the TC.

Identifying the G Synoptic Pattern requires: (i) there is present in the vicinity of the TC a particular type of monsoonal circulation that will hereafter be termed a monsoon gyre; and (ii) the TC has a position relative to the monsoon gyre so that its steering is directly influenced by the monsoon gyre.

Multiple (M) Tropical Cyclone Synoptic Patterns are identified when two TCs are: (i) in proximity to each other (less than about 20° lat.), but with a separation distance that would not result in a significant binary interaction, which generally occurs at less than 10°-12° lat. (Brand 1970; Dong and Neumann 1983); (ii) oriented approximately east-west; and (iii) sufficiently close (north or south) to the ridge axis that the height gradient between the western (eastern) TC and the eastern (western) ridge circulation subjects the eastern (western) TC to moderately strong (10-15 kt) and predominately poleward (equatorward) steering flow. However, it is possible for additional TCs to be in proximity without setting up competing M Synoptic Patterns.

2. Synoptic Regions

The Synoptic Regions are conceptual models to classify areas within the Synoptic Patterns that determine the environmental steering of the TC (Fig. 2). The Synoptic Regions are generally described in a specific orientation relative to ridge circulations with well-defined boundaries. A total of six Synoptic Regions are identified within the four Synoptic Patterns. Several of the regions are found in more than one pattern.

The Standard Synoptic Pattern is comprised of the Dominant Ridge (DR), Weakened Ridge (WR), and Accelerating Westerlies (AW) Synoptic Regions. The DR Region involves locations satisfying the following: (i) poleward of the monsoon or equatorial trough axis, or poleward of about 5° lat. if no trough exists; (ii) equatorward of the axis of an east-west oriented ridge circulation that tends to dominate the motion of the TC by producing roughly easterly steering of about 10-15 kt; and (iii) not in the vicinity of a "significant" break along the ridge axis that weakens the steering flow and makes it more southerly. The WR Region, which is unique to the S Pattern, consists of all locations that are: (i) equatorward of the subtropical ridge axis; (ii) east of the center of a break in the ridge; and (iii) close enough to the break to be in roughly weak (5-8 kt) and southeasterly-to-southerly steering. The AW Region consists of the locations with a Synoptic Pattern that are: (i) poleward of the ridge axis, and generally within about 10° lat. of the ridge axis; and (ii) east of the ridge-break neutral point.

The N Synoptic Pattern only contains two Synoptic Regions, the North-oriented (NO) and the AW. The NO Synoptic Region consists of locations that are in a predominantly southerly flow to the west of the anomalous, meridionally-broad ridge circulation. The AW Synoptic Region of the N Synoptic Pattern is fundamentally the same as in the S Synoptic Pattern.

The G Synoptic Pattern contains three regions. The NO and AW Synoptic Regions are essentially the same as previously described for the N and the S Patterns. The DR Region of the G Pattern is the region to the northwest of the monsoon gyre where east-northeasterly steering occurs due to the gradient between the gyre and the ridge to the north.

The M Pattern contains the Northerly Flow (NF) and the Southerly Flow (SF) Regions that are symmetric about a north-south line running through the centroid between the TCs. The SF (NF) Region consists of locations that are: (i) in the predominantly southerly (northerly) environmental flow in the vicinity of the line running from the center of the western (eastern) TC to the center of the eastern (western) ridge circulation; and (ii) no closer than about 10° lat. to the western (eastern) TC.

C. TRANSITIONAL MECHANISMS

A transition involves a change from one Synoptic Pattern to another, or from one Synoptic Region to another Region within the same Pattern. The Environment Structure may be altered by either the TC or factors within the environment. On the one hand, TC-Environment transformations (Fig. 3) are changes to the Environment Structure that are the consequence of the TC(s). On the other hand, the environmental effects (Fig. 4) are changes to the Environment Structure that are caused by related factors of the environment that would exist even if the TC were not present.

D. METHODOLOGY

The determination of the Environment Structure utilizing operational analyses is the first goal in the Numerical Guidance Analysis phase. CE recommend varying the optimum steering level based on the TC intensity conceptual model. The Numerical Guidance analyses fields most readily available at the Naval Postgraduate School are at 500 mb. Thus, the 500 mb NOGAPS analyses from FNMOC are annotated with the warning and past 12-, 24-, and 36-h positions, translation speeds, and intensities (Fig. 5) based on best track files from the appropriate forecast centers. Geostationary satellite infrared (IR) and visible (VIS) imagery were also utilized, when available.

E. PLAN OF THESIS

This thesis consists of two distinct parts. The author was trained in the Systematic Approach and then participated as one of three trainees in a reproducibility test, which was a "proof of concept" as applied to the western North Pacific for the 1989-93 seasons.

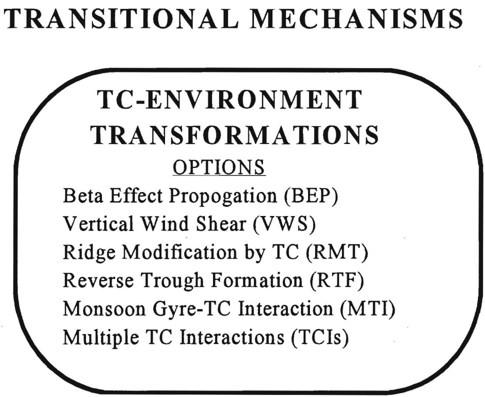


Figure 3. Transitional mechanisms initiated by various combinations of Environment Structure and TC Structure creating the above identified TC-Environment transformations for the western North Pacific basin (from Carr et al. 1995).

TRANSITIONAL MECHANISMS

ENVIRONMENT EFFECTS

OPTIONS

Advection by Environment (ADV)
Monsoon Gyre Formation (MGF)
Monsoon Gyre Dissipation (MGD)
Subtropical Ridge Modulation (SRM)

Figure 4. Transitional mechanisms initiated by factors within the environment (excluding the TCs) identified for the western North Pacific basin (from Carr et al. 1995).

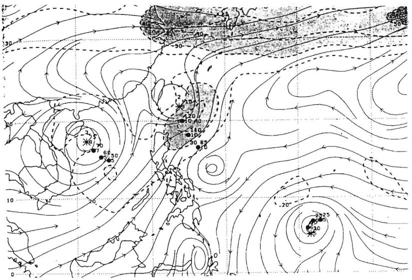


Figure 5. Example of a FNMOC 500 mb streamline and isotach (kt) analysis with present (asterisk) and past 12-, 24-, and 36-h positions (dots) of three tropical cyclones at 1200 UTC 27 June 1992. Isotach contours are at 10 kt beginning with 20 kt and values greater than 30 (50) kt have light (heavy) shading. Cyclone intensities (kt) are adjacent to the positions, and 12-h translation speeds (kt) are between the past postions.

This test will be summarized in the next Chapter (more detail is given in Carr et al. 1995). The second part of the thesis is the extension of the Numerical Guidance Phase to the eastern and central North Pacific tropical cyclones. Chapter III will describe this second part.

II. REPRODUCIBILITY TEST

A. INTRODUCTION

The Synoptic Patterns and Regions developed in the Systematic Approach of Carr and Elsberry (1994; hereafter CE) were the focus of the reproducibility test. The primary goal of conducting the reproducibility test was to ascertain whether trainees could determine the correct Synoptic Patterns/Regions, because correct identifications of these Patterns/Regions are an essential step in the application of the Systematic Approach. Another objective was that a study of the incorrect identifications by the trainees would highlight deficiencies in the descriptions of the Patterns/Regions or in the training phase of the program. That is, trainee misconceptions, difficulty in identifying Patterns/Regions, and misclassifications based on the conceptual models were anticipated, and do not necessarily indicate the knowledge base of the Systematic Approach was flawed. Rather, it may simply indicate deficiencies in the descriptions of the conceptual model(s), or in the training phase.

B. TRAINING

The three trainees had no previous tropical cyclone forecast experience. Their instruction in the Systematic Approach was to first read a draft version of CE. After each assigned reading, discussions were conducted to ensure the trainees possessed a thorough understanding of the material. Feedback and questions from the trainees contributed to improvements in the descriptions in the final version of the Carr and Elsberry technical report.

The second phase of the training began with some relatively easy storms from 1989, and the trainees were allowed to work together to apply the conceptual models of the Systematic Approach. Upon completion, a detailed debrief was conducted with the instructor that reinforced the principles. The trainees then moved on to another set of 1989 cases where they worked independently. This second set of cases was to establish whether the trainees were adequately trained to proceed with the reproducibility test. Again, an extensive debrief was conducted to intercompare Pattern/Region assignments, and where differences existed, to review each individual's reasoning. After this second set of cases was completed, a determination was made to proceed to the actual reproducibility test.

C. REPRODUCIBILITY TEST

1. Synoptic Pattern/Region Combinations

This test documents the trainees' ability to identify correctly the Synoptic Pattern/Region combinations. Recognition of these Patterns/Regions constitutes the backbone of the Systematic Approach in producing an improvement over present TC track forecast techniques.

The percent correct identifications of each trainee (A-C) for a four-year (1990-1993) total for each of the ten possible Synoptic Pattern/Region combinations is shown in Table 1. Notice the overall combined correct percent identifications for the trainees was

Table 1. Percent correct identifications for each trainee (A-C) for the four-year (1990-1993) total for each of the ten Synoptic Pattern/Region combinations. The right column lists each trainee's overall percent correct identifications. The combined row shows percent correct for all three trainees combined. Below this row is the combined number of Pattern/Region combinations found in the four-year sample. In parentheses is the frequency of each Pattern/Region combination for the four years (from Carr et al. 1995).

		S/DR	S/WR	S/AW	N/NO	N/AW
	A	93.3	64.1	51.7	83.2	74.2
TRAINEES	**B**	94.7	16.7	8.8	70.8	71.3
	C	93.0	78.8	47.4	40.6	22.2
	Combined	93.6	53.3	35.6	65.0	56.7
		773	36	25.5	289.5	115.5
		(54.0)	(2.5)	(1.8)	(20.2)	(8.0)

		G/NO	G/DR	G/AW	M/NF	M/SF	OVERALL
	A	69.9	44.4	25.0	82.6	75.0	84.6
TRAINEES	**B**	29.3	35.5	23.8	25.0	59.1	76.9
	C	42.4	27.6	40.0	82.6	79.3	71.2
	Combined	47.8	34.4	29.5	66.7	72.0	77.5
		91.5	29.5	23.0	23.0	27.5	1434
		(6.5)	(2.0)	(1.6)	(1.6)	(1.9)	

77.5% for the Synoptic Patterns/Regions. This ability of the trainees without previous TC forecasting experience to recognize these Patterns/Regions reinforces the validity of the Systematic Approach. The test is important to the application of the Systematic Approach because this component involves subjective thought processes in the recognition and assignment of the Synoptic Pattern/Region combinations.

2. Synoptic Pattern/Region Transitions

a. Transitions

Whereas properly identifying the correct Synoptic Pattern and Region is important, of even greater importance is the proper recognition of when a cyclone transitions from one Synoptic Pattern/Region combination to another. Because such transitions will normally lead to significant changes in the track of the cyclone, recognition of an upcoming transition and the timing of that transition are tantamount to accurate track forecasts. It is in this area of reducing potential forecast errors associated with changing storm motion that the Systematic Approach can be most useful in its application. The hypothesis of CE is that a properly equipped forecaster can recognize Pattern/Region transition in NOGAPS forecast fields, select the objective aid forecast tracks that are consistent with the anticipated transition, and formulate an official forecast that modifies those objective tracks for expected transition-related biases.

The scoring results are summarized in Table 2 by individual year and a 4-y combined total. The numbers of transitions in 1990 through 1993 are 15, 34, 60, and 32, respectively. The tables have a combined total of 423 transitions since each of the three

Table 2. Combined numbers of transitions that should have been detected by the three trainees, with separation into correct, similar, missed, false and flip-flops for each year and the 4-y combined total (from Carr et al. 1995).

Year (Transitions)	Correct	Similar	Combined	Missed	False	Flip-flop
1990 (45)	28	13	41	4	3	9
1991 (102)	42	40	82	20	12	17
1992 (180)	92	52	144	36	6	24
1993 (96)	42	33	75	21	5	14
Combined (423)	204 (48.2%)	138 (32.6%)	342 (80.9%)	81 (19.1%)	26 (6.1%)	64 (15.1%)

trainees should have detected 141 transitions. That is, the combined sums for the individual years will be 45, 102, 180, and 96, respectively. Unless otherwise identified, all future references to the number of transitions for the individual years and combined 4-y total will be the total for all three trainees.

b. Timing

Another important result is the trainee's timing of the transition. While identifying that a transition is occurring is extremely important, correctly timing the transition is also of importance. Helping the forecaster properly identify the timing of the transition is a goal of the Systematic Approach training.

A histogram of the 342 correctly and similarly identified transitions for the three trainees for the 4-y combined data set is given in Fig. 6. These correct or similar

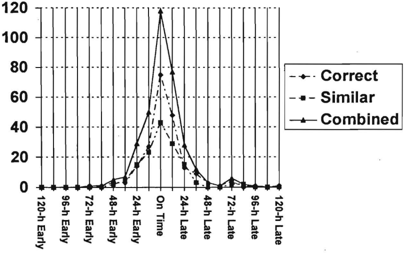


Figure 6. Histogram of timing of correct and similar transitions identified by the three trainees for the 4-y combined data set (from Carr et al. 1995).

transitions were identified "on time" in 118 cases. However, one transition was identified 120 h late. Of the 342 correct/similar transitions, 245 (71.6%) were identified either 12 h late, on time, or 12 h early. These 245 well-timed transitions represent 58% of the 423 transitions that occurred in the 4-y combined data set. The transition timing distribution for the trainees is slightly shifted toward the late identifications. This is understandable considering the trainees did not have the opportunity of looking backward and correcting for a missed transition.

If the "acceptable" timing windows for transitions is expanded to ±24 h, the number of correct/similar transitions is still only 302. This expanded window would result in 71.4% of the 423 transitions being identified as correct/similar transitions.

D. REVISIONS

The training for this reproducibility test of recognizing the TC-Environment situation occurred as the CE report on the Systematic Approach was being finalized. The proposed enhancements to be made to the training are based on the lessons learned during the reproducibility test. Two sources were utilized to apply the principles of the Systematic Approach to the TC-Environment situation. The first of these were the FNMOC NOGAPS analyses with the past tracks superposed (Fig. 5). The second was the geostationary satellite infrared imagery that was utilized both as a validation of the features in the numerical analyses and to provide additional information on the TC-Environment situation.

The Gyre (G) Pattern definitions and the associated Regions as explained in CE were not applied well in this reproducibility test (see Table 1). The trainees' frequency of detection of the G Pattern was only 46.0%. A better or more consistent use of the satellite imagery in detection of the G Pattern was the major impetus for this revised training section. The importance of utilizing the geostationary satellite imagery in conjunction with the NOGAPS analyses in validating "large-scale" synoptic features cannot be over-emphasized. CE state one premise of the Systematic Approach is to introduce the element of human reasoning based on a dynamic, meteorological knowledge base so that the numerical guidance is not the only source of information to the forecaster. The geostationary satellite imagery allows forecasters to develop a conceptual model independent of the numerical analyses. A subtle point in the Systematic Approach is the forecasters' ability to separate the individual effects of the TC from the environment and vice versa. In other words, a forecaster must be able to envision the synoptic environment without the TC present. As with the other Synoptic Pattern conceptual models, the forecaster must recognize that actual G Patterns depicted in NOGAPS analyses may vary from the idealized schematics found in CE.

A more consistent use of the geostationary satellite imagery in conjunction with the NOGAPS analyses should allow the forecaster to assign the correct TC-Environment Structure. The deficiencies revealed by the reproducibility test emphasizes the importance of utilizing concurrently these sources of information.

E. SUMMARY

The original technical report of CE was based heavily on the operational TC forecasting experience of L.Carr during the 1990 and 1991 western North Pacific seasons. The reproducibility test performed two tasks. First, the validity of the Systematic Approach was reinforced by the success of the three trainees in recognizing the Patterns/Regions. While the comprehensive evaluation of many years of daily analyses exposed some problems and ambiguities in the Systematic Approach descriptions and in the trainees training, the consensus of the trainees and developers is that the TC-Environment conceptual models are sufficient to characterize nearly all of the variations of

TC-Environment Structure that occur in the western North Pacific basin. Refinements of the Systematic Approach have been made (Carr et al. 1995) based on the reproducibility test, and the updated Environmental Structure framework of the Systematic Approach is summarized in Figs. 2-4 above.

The second output of the reproducibility test was the assistance of the trainees in creating a five-year climatology data set. The addition of a climatology data set to the meteorological knowledge basis and TC-Environment conceptual models in the Systematic Approach allow the creation of new rules of thumb to be used for TC track forecasting in the western North Pacific.

III. APPLICATION TO EASTERN AND CENTRAL PACIFIC

A. INTRODUCTION

The Systematic Approach of Carr and Elsberry (1994; hereafter CE) was developed for the western North Pacific. CE hypothesized that the meteorological framework of the Systematic Approach would be generally applicable to other tropical basins of the world. For this reason, the Environment Structure developed in CE was used as the starting point for analysis of the eastern and central North Pacific Synoptic Patterns and Regions. Nevertheless, it was anticipated that differences would be found between the western North Pacific and the eastern and central North Pacific, which would require the modification of the Synoptic Patterns and Regions developed in CE, as well as the introduction of new Synoptic Patterns and Regions.

The Environment Structure of the eastern and central North Pacific TCs generally tends to resemble one of the four Synoptic Patterns outlined in Fig. 1. The similarities and differences will be summarized below in Sections C and D. In addition, the TC positions within the defined Synoptic Regions (Fig.1) are also similar to most of the Synoptic Regions of the western North Pacific. In Section B of this Chapter, the methodology in producing the eastern and central North Pacific data base will be described. The similarities with (Section C) and the differences from (Section D) the western North Pacific will be examined, which will lead to the presentation in Section E of the newly developed Synoptic Patterns/Regions for the eastern and central Pacific. Finally, a climatological summary of the frequencies of occurrence, associated TC tracks, and preferred paths of transitions, during the 1990-1993 eastern and central North Pacific seasons will be presented and discussed in Section F.

B. METHODOLOGY

The data base consists of all TCs in the eastern and central North Pacific that existed during four years (1990-1993). The numerical analyses utilized are from the U.S. Navy Fleet Numerical Meteorology and Oceanography Center (FNMOC) in Monterey, CA. The 500 mb analyses from FNMOC were annotated with the warning and past 12-, 24-, and 36-h positions, translation speeds, and intensities (Fig. 7) based on best track files

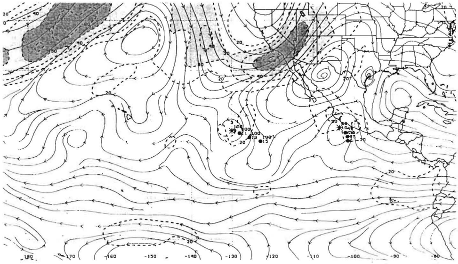


Figure 7. Example of a FNMOC 500 mb streamline and isotach (kt) analysis with present (asterisk) and past 12-, 24-, and 36-h positions (dots) of two tropical cyclones at 0000 UTC 25 June 1991. Isotach contours are at 10 kt beginning with 20 kt and values greater than 30 (50) kt have light (heavy) shading. Cyclone intensities (kt) are adjacent to the positions, and 12-h translation speeds (kt) are between the past positions.

from the appropriate forecast centers. Due to the availability of FNMOC analyses only at 500 mb for the entire 4-year period, 500 mb was chosen as the steering level vice the optimum steering level based on storm intensity (CE). When available, FNMOC 700 mb analyses were used for dissipating TCs. Geostationary satellite infrared (IR) and visible (VIS) imagery were also utilized. Geostationary satellite imagery not accessible locally were kindly provided by the Department of Meteorology, University of Hawaii from the files at the Central Pacific Hurricane Center, and other imagery was obtained from the National Hurricane Center archives.

C. SIMILARITIES WITH WESTERN NORTH PACIFIC

As is the case for the western North Pacific, the structure of the mid-tropospheric subtropical ridge (hereafter, subtropical ridge) is the prominent feature for the eastern and central North Pacific. In the western North Pacific, the subtropical ridge is approximately zonally-oriented as is represented in the conceptual model of CE. In this idealized S Pattern, an east-west oriented subtropical ridge has tradewind easterlies on the equatorward side and mid-latitude westerlies on the poleward side. This idealized S Pattern is intended to be a template that must be adapted to the synoptic situation. The important and frequently observed variants of the S Pattern for the western North Pacific are also observed for the eastern and central North Pacific. Those variations include:

- absence of a significant break in the ridge in the general vicinity of the TC;

- different latitudes for the eastern and western ends of the subtropical ridge circulations, so that the ridge axis may vary from west-southwest to east-northeast or from west-northwest to east-southeast; and
- unequal meridional extent of the subtropical ridge circulation on either side of the main break in the ridge.

As stated in CE, the first variant produces predominantly easterly steering provided the S Synoptic Pattern persists. It is the remaining two variants that comprise the bulk of the synoptic situations found in the eastern and central North Pacific.

The subtropical ridge in the eastern North Pacific extends westward from the North America continent into the eastern and occasionally the central North Pacific not unlike the subtropical ridge of the western North Pacific that extends eastward from the Asian continent. Both of these subtropical ridges are rather permanent features that appear to be anchored to the North American or Asian continents, respectively. Whereas the subtropical ridge of the western North Pacific is generally east-west oriented, the subtropical ridge of the eastern and central North Pacific is predominantly tilted in one of the two orientations listed above. These orientations of the subtropical ridge for the eastern and central North Pacific, specifically the different latitudes for the eastern and western circulations, are the main features in determining the existence of the Synoptic Patterns/Regions set forth by CE.

The North-Oriented (N) Synoptic Pattern of CE is distinguishable in the eastern and central North Pacific. The conditions for identification of the N Pattern are listed in Chapter I.B1. In the idealized N Pattern for the western North Pacific, CE describe the “reverse-oriented” monsoon trough as one of several climatological modes that is commonly found in the western North Pacific. Whereas the western North Pacific N Pattern is a manifestation of the monsoon trough, the eastern and central North Pacific N Pattern results from mid-latitude, large amplitude, waves creating modifications in the subtropical ridge. These modifications to the subtropical ridge are outlined in Figs. 3-4 as either TC-Environment effects or Environment effects. The eastern and central North Pacific TC-Environment Structure, specifically the N Pattern, is most commonly modified via the Subtropical Ridge Modulation (SRM) as outlined in Fig. 4. As such, the idealized N Pattern for the eastern and central North Pacific will be modified in the next section to reflect the resultant Environment Structure changes due to the SRM.

Finally, the Multiple (M) Tropical Cyclone Synoptic Pattern of CE is also observed in the eastern, but not in the central, North Pacific. The requirements for classification of the M Synoptic Pattern are also listed in Chapter I.B1 above. In the M Pattern for the western North Pacific, the eastern TC is acting to inhibit the recurvature of the western TC, and the western TC is concurrently acting to encourage the recurvature of the eastern TC. Although the requirements for multiple TCs are satisfied in the eastern North Pacific in this sample, the condition for the two TCs to be approximately east-west oriented reduces the number of TC-Environment Structures that are characterized as the M Synoptic Pattern in the eastern North Pacific. Once again, the orientation of the subtropical ridge for the eastern North Pacific requires a modification to the M Pattern conceptual model, which will be presented in Section D of this chapter.

D. DIFFERENCES FROM WESTERN NORTH PACIFIC

The orientation and amplitude of the subtropical ridge in the eastern and central North Pacific is a dominant factor in determining the Environment Structure in these TC basins. The importance of the subtropical ridge and its orientation (hereafter, tilt) is paramount in understanding the differences found in the eastern North Pacific. In the idealized S Pattern for the eastern North Pacific (Fig. 8), the easterly environmental flow

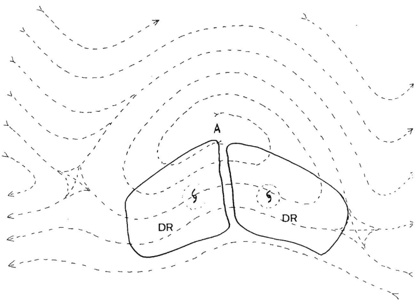


Figure 8. Schematic for the Standard (S) Synoptic Pattern conceptual model for the eastern and central North Pacific. TC symbols and dotted concentric circles denote possible positions for TCs within the S Pattern. The dashed boxes represent the two subregions within the Dominant Ridge (DR) Region.

equatorward of the subtropical ridge is dominant. The difference between this conceptual model and that proposed for the western North Pacific lies in the tilt of the subtropical ridge. Whereas the flow equatorward of the subtropical ridge for the western North Pacific is generally easterly, the flow pattern in the eastern North Pacific equatorward of the subtropical ridge is separable into two distinct subregions. These two subregions equatorward of the subtropical ridge are characterized in Fig. 8 as the easterly half with southeasterly flow and the westerly half with northeasterly flow. Unlike the S Pattern and DR Region of the western North Pacific, the S/DR Pattern/Region combination for the eastern and central North Pacific exhibits distinctly different tracks for TCs found in the eastern or western subregions of Fig. 8. These tracks and associated steering will be highlighted in Section F.

One major difference in the eastern and central North Pacific is the importance of the Subtropical Ridge Modification (SRM) transitional mechanism, which describes the impact of the mid-latitude transitory waves on the subtropical ridge. The SRM conceptual model was one of the refinements to the Systematic Approach made by Carr et al. (1995). In the western North Pacific, the mid-latitude waves did not appear to be very strong and had less impact on the subtropical ridge. However, the mid-latitude troughs and ridges in the eastern and central North Pacific are one of the more important factors in forecasting the track of a TC. The eastern and central North Pacific mid-latitude waves appear to be stronger and have a greater impact on the subtropical ridge than their western North Pacific counterparts.

Only three of the four western North Pacific Synoptic Patterns are found in the eastern/central North Pacific because the Monsson Gyre (G) Pattern is not found. A somewhat similar type of circulation found in the eastern/central North Pacific has lead to the introduction of a new Synoptic Pattern called the Low (L) Pattern. The L Pattern and its associated Synoptic Regions will be described in detail in Section E of this chapter.

A new Synoptic Region within the S Pattern was necessary to account for eastern/central North Pacific TCs leaving the WR Region that did not quickly transition to the AW Region as in the western North Pacific. Two possible explanations for the lack of a quick transition from the WR to AW Region are: (i) tropical cyclones that break through the subtropical ridge in the eastern/central North Pacific tend to do so farther south from the strongest mid-latitude westerlies than in the western North Pacific, or (ii) the higher amplitude mid-latitude waves have weaker winds associated with them. Consequently, the eastern/central North Pacific TCs often move in a northeastward direction for significant periods of time at translation speeds less than 15 kt, which had not been described in the Systematic Approach based on western North Pacific cases. This new Synoptic Region in the eastern/central North Pacific S Pattern will be described in Section E of this chapter.

The conceptual model by CE for the N Pattern of the western North Pacific requires modification to better illustrate the structure (Fig. 8) of the subtropical ridge in the eastern/central North Pacific. The required conditions for the N Pattern of the western North Pacific are listed in Chapter I.B. The N Pattern conceptual model for the eastern/central North Pacific is presented in Fig. 9. The mid-tropospheric trough in the

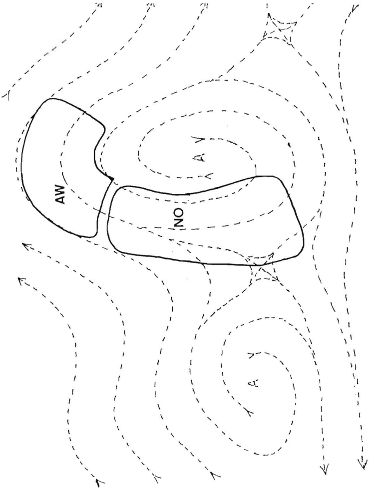


Figure 9. Schematic of the eastern/central North Pacific North-oriented (N) Pattern conceptual model.

eastern/central North Pacific's conceptual model is not the "reverse-oriented" monsoon trough, which plays an integral part of the western North Pacific's N Pattern as stated in CE. Rather, this is a mid-latitude trough extending into the subtropics. The modification in the conceptual model for the eastern/central North Pacific is a result of the influence of the mid-latitude waves, and the Subtropical Ridge Modulation (SRM) is the primary mechanism for changing the Environment Structure. The Ridge Modification by a large/medium TC (RMT) does not have as much influence due to the smaller size of TCs in the eastern/central North Pacific. The reduced influence of RMT, coupled with the mid-latitude waves found poleward of the subtropical ridge, creates an Environment Structure that reflects undulations in the mid-latitude westerlies found westward and poleward of the main subtropical ridge.

The idealized M Pattern of CE for the western North Pacific is also modified to reflect the subtropical ridge structure in the eastern North Pacific. The requirements for classification of the M Pattern in the western North Pacific are listed in Chapter I.B. The requirement that one TC be sufficiently close to the subtropical ridge to produce a height gradient across the second TC is one factor that requires conceptual model modification for the eastern North Pacific. The other factor deals with the smaller size of TCs in the eastern North Pacific. To create a height gradient sufficient to produce the environmental steering of the M Pattern, the TC pair must exist sufficiently close to the subtropical ridge. The existence of a TC pair equatorward of the tilted subtropical ridge in the eastern North Pacific may not be sufficient to generate the required height gradient despite their proximity and an east-west ridge orientation. On the other hand, two TCs can be sufficently close (less than about 20° lat.) and satisfy the other requirements of the M Pattern, but not exhibit the environmental steering as depicted in the M conceptual model of CE. It is hypothesized that the smaller horizontal extent of TCs in the eastern North Pacific is a factor when considering proximity. These two factors (height gradient and size) resulted in M Patterns in the eastern North Pacific that were more transitional than those in the western North Pacific.

The eastern/central North Pacific does not have a western boundary current as does the western North Pacific. For this reason, warm water is generally not observed as far poleward as in the western North Pacific. In this sample, TCs rarely existed poleward of 30° lat. in either the eastern or central North Pacific. In contrast, TCs of the western North Pacific routinely exist poleward of 30° lat., which allows these TCs to transition to other Environment Structures associated with the mid-latitude westerlies. The poleward-moving TCs in the eastern/central North Pacific tend to dissipate before reaching the mid-latitude westerlies, presumably due to the lack of warm tropical water in these regions, and also large vertical wind shear between low-level easterlies and upper-level westerlies. For example, the sea-surface temperature (SST) from the weekly National Meteorological Center (NMC) Optimum Interpolation SST analysis at the positions of dissipating TCs during the 1993 season are summarized in Table 3. The 1993 season is chosen because the SST charts were readily available at NPS. Although the sample is not complete, low SSTs clearly exist at the time of TC dissipation in the eastern/central North Pacific. The

Table 3. The eastern North Pacific TCs of 1993 and the approximate (+/- 2°C) sea-surface temperature (SST) during the dissipation of each TC.

TC Name	sea-surface temperature (SST) (°C)
Adrian	26
Beatriz	landfall
3-E	landfall
Calvin	23
Dora	26
Eugene	26
Fernanda	24
Greg	25
Hilary	landfall
Irwin	26
Jova	25
Kenneth	24
Lidia	landfall
14-E	26
Max	27
Norma	26
17-E	24

vertical wind shear effects on TC dissipation as well as a transitional mechanism (Fig. 3) will be discussed in Section F.

The final difference involves the topography along the Central American coast, which appeared to influence four TC tracks in this four-year sample. For example, TC Calvin during 1993 is a good example of the topographic effect. Zehnder (1993) attributes the track deflections associated with the Sierra Madre topography to modifications of the beta gyres through vortex stretching. Horizontal convergence and divergence as the air flows over the topography may be inferred from the the conservation of potential vorticity

$$\frac{\zeta_r + f}{D} = \textit{Constant},$$

where ζ_r is the relative voticity, f is the Coriolis parameter, and D is the column depth between two isentropic surfaces. For example, the airflow descending (ascending) west of the Sierra Madre of Mexico will experience vertical stretching (compression) and a larger (smaller) vertical depth (D). Conservation of potential vorticity requires the relative vorticity (ζ_r) to increase (decrease) to offset this depth increase (decrease). This tendency to increase (decrease) the relative vorticity north-northeast (south-southeast) of a TC west of the Sierra Madre adds to the vorticity tendency associated with the environmental steering effect. Specifically, a cyclonic (anticyclonic) gyre to the north-northeast (south-southeast) would produce an additional vorticity tendency associated with a steering toward the topography. Cyclonic (anticyclonic) curvature of the streamlines west of the Sierra Madre to the north (southeast) of TC Calvin in Fig. 10 is consistent with the potential vorticity conservation idea. The relative magnitude of the topographic contribution to the motion versus the steering effect is unknown because a unique method of separating the two possible contributions is not available. Clearly, the topographic contribution will be a function of the separation distance and the size of the TC circulation, because the air must be forced up or down the sloping topography to induce vertical compression or stretching of columns.

E. NEW SYNOPTIC PATTERN/REGION

Descriptions of a new Synoptic Pattern and a new Synoptic Region in the Systematic Approach for application to the eastern and central North Pacific basin are given in the following sections.

1. Low Synoptic Pattern

A new Low (L) Synoptic Pattern is proposed for the eastern/central North Pacific TCs. This Synoptic Pattern was not a part of the original Systematic Approach of Carr and Elsberry (1994), or in the five-year climatology of Carr et al. (1995). The L Synoptic Pattern forms from an upper-level low or cyclonic circulation that has sufficient strength to extend downward to the mid-troposphere. Because this induced low (trough) often penetrates into a mid-level ridge (Fig. 11), it may appear as a relatively large, closed cyclonic circulation that is completely surrounded by the ridge. Upper- and mid-

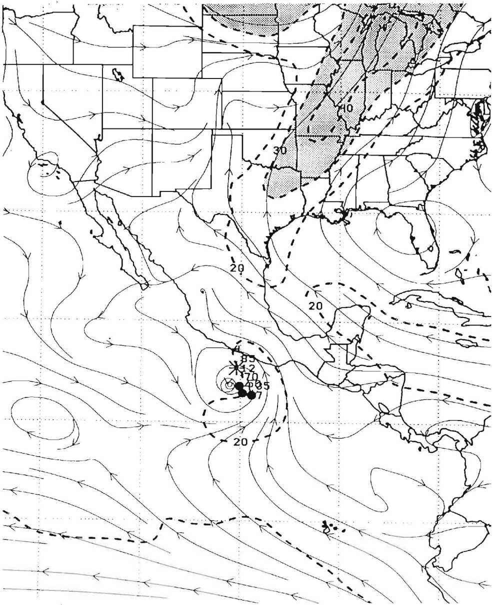


Figure 10. NOGAPS 850 mb streamline and isotach (kt) analyses as in Fig. 7 for Hurricane Calvin at 0000 UTC 6 July 1993.

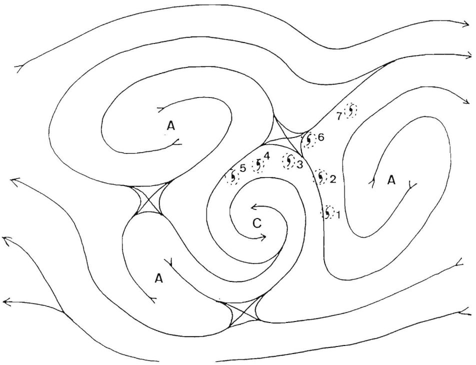


Figure 11. Schematic of the Low (L) Synoptic Pattern conceptual model. TC symbols and dotted concentric circles denote possible positions for TCs within the L Pattern.

tropospheric low pressure systems occur frequently (rarely) in the central (eastern) North Pacific during the summer months.

The persistence or strength of this Synoptic Pattern may be greatly aided or hindered by the mid-level transitory cyclones and anticyclones passing to the north. In the schematic (Fig. 11) of the 500 mb streamlines for the L Synoptic Pattern, the amplitude of the anticyclones surrounding the cyclonic circulation and embedded TC will also vary in response to transitory mid-latitude wave trains. These transitory waves may have a large impact on the continuation or termination of the L Pattern, which does not tend to persist very long. For these reasons, the forecaster must be aware that the L Pattern depicted in NOGAPS analyses will vary somewhat from the idealized schematic depending on the positions and amplitudes of mid-latitude features with respect to the cyclonic circulation.

The TC-Environment Structure will be classified as a L Synoptic Pattern whenever: (i) a TC is embedded in a cyclonic circulation that is significantly larger than the TC; and (ii) the TC has a position relative to the cyclonic circulation as suggested by the TC symbols 1-7 in Fig. 11. While this L Synoptic Pattern appears similar to the Monsoon Gyre (G) Synoptic Pattern of the western North Pacific (see CE), the L Synoptic Pattern differs in its formation, maintenance, and life cycle. In addition to being smaller in size and at a higher latitude than the monsoon gyre, the mid-tropospheric cyclonic circulation is a downward reflection of a cold-core upper-tropospheric low, rather than an upward reflection of a warm-core monsoonal circulation. Thus, the amplitude and motion of the mid-tropospheric cyclonic circulation in Fig. 11 will be determined to a large extent by the dynamics of the upper-tropospheric system. Such systems usually originate as cut-off lows that then drift west-southwest and dissipate in the subtropics or tropics.

The three Synoptic Regions associated with the eastern or central North Pacific L Synoptic Pattern are shown in Fig. 12. The North-Oriented (NO) Synoptic Region is fundamentally the same as in the N Pattern, although the western boundary of the NO Region in the L Pattern curves around the center of the cyclonic circulation. Although not actually observed in the four-year sample, a Dominant Ridge (DR) Synoptic Region is hypothetically possible in which the TC undergoes east-northeasterly steering primarily due to the gradient between the cyclonic circulation and the subtropical anticyclone cell to the north and northwest. In this sense, the L/DR Pattern/Region is analogous to the G/DR Pattern/Region in Fig. 2. Another possible, but not observed, Synoptic Region is the AW region, which occurs when the TC breaks through a weakness in the subtropical ridge to the north of the cyclonic circulation. The inherent dissipative nature of cold lows, and consequently the short life span of the L Synoptic Pattern, are believed to be why the DR and AW Regions are not observed. In order for a TC to reach one of these Regions from the NO Region, the L Pattern would have to persist for 2-3 days while the TC moves around the cyclonic circulation. The observed life span of the L Pattern in this four-year sample is about 36-48 hours.

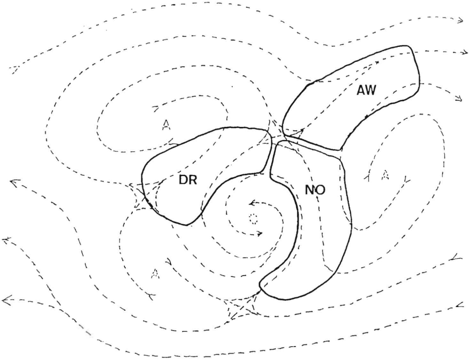


Figure 12. Schematic of the Low (L) Synoptic Pattern conceptual model, except with the boundaries of the associated Synoptic Region conceptual models added (solid lines).

2. Weak Westerlies Synoptic Region

A new Synoptic Region within the Standard (S) Synoptic Pattern is defined as the Weak Westerly (WW) Synoptic Region (Fig. 13). The WW Synoptic Region is unique to the S Pattern. The WW Region, which is an intermediate Region between the WR and AW Regions, is required for the eastern/central North Pacific storms that do not move directly into the strong westerly mid-latitude flows as in the western North Pacific. The first characteristic of the WW Region is that the TC is moving slower than 15 kt. Two variations in the direction of TC movement are found in the WW Region. The first variation follows a transition from the WR Region, which in the western North Pacific would immediately lead to the AW Region. After proceeding north of the ridge axis, a TC transitioning from the WR Region will tend to move northeastward through eastward. The second variation in the TC direction for the WW Region occurs after the storm has passed east of the north-south subtropical ridge axis and begins to move in a southeastward direction on the east side of the ridge. This normally occurs if the TC recurves at a latitude well south of the strong westerly wind flow that occurs farther north in the eastern/central North Pacific. In both direction variations, the translation speed of the TC should be less than 15 kt. The direction of the TC will depend on the position of the storm with respect to the subtropical ridge to its south.

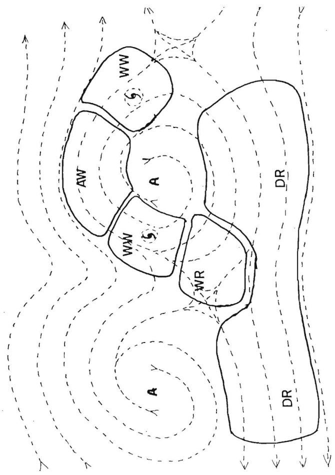


Figure 13. Schematic of the Weak Westerly (WW) Synoptic Region conceptual model. TC symbols and dotted concentric circles denote possible positions of a TC.

F. CLIMATOLOGY OF SYNOPTIC PATTERNS/REGIONS

1. Pattern and Region Frequencies

This preliminary (based on only four years) climatology of the Environment Structure characteristics is intended to give forecasters an idea of the frequency of these Synoptic Patterns and Regions. Table 4 is a list of the possible Pattern/Region combinations that characterize the Environment Structure in the Systematic Approach application to the eastern and central North Pacific. Each of the 1358 characterizations is counted as one occurrence of the particular Pattern/Region. For transitional situations with dual assignments, each Pattern/Region is counted as one half.

a. Pattern Frequency

The four-year frequency of TCs in each of the four Synoptic Patterns is shown in Fig. 14. The Standard (S) Synoptic Pattern is by far the most prevalent (93%) Pattern. This is much larger than the 58% of the S Patterns in the western North Pacific. This high percentage is not surprising since TCs in the S/DR Pattern/Region can remain equatorward of the subtropical ridge for long periods, particularly when the subtropical ridge is extending southwest of the North American continent. In 3% of the 1358 cases, the TC is in a North-oriented (N) Pattern (Fig. 9), which is west of the prominent subtropical ridge and has a southerly environmental flow. This small frequency is considerably down from the 27% of N Patterns in the western North Pacific. The reduced number of N Patterns is probably due to the strength and prevalence of the eastern and central subtropical ridge relative to weaker peripherial ridges that are generated by the

Table 4. Synoptic Pattern/Region combinations (including hypothetical combinations not observed) that characterize the Environment Structure in the eastern/central North Pacific Systematic Approach.

PATTERNS	REGIONS
S - Standard	DR - Dominant Ridge WR - Weakened Ridge WW - Weak Westerlies AW - Accelerating Westerlies
N - North-oriented	NO - North-oriented AW - Accelerating Westerlies
L - Low	NO - North-oriented AW - Accelerating Westerlies
M - Multiple TCs	NF - Northerly Flow SF - Southerly Flow

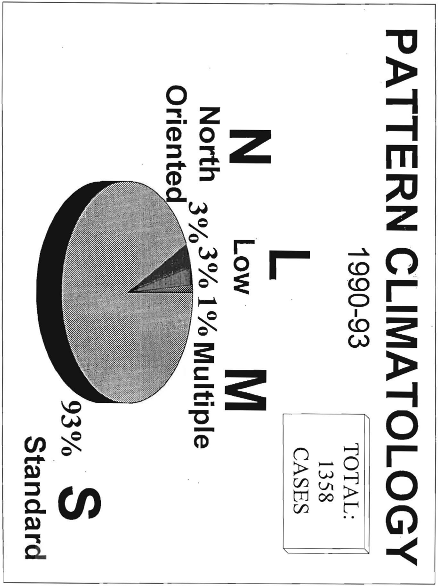


Figure 14. Percentage of the 1358 characterizations of the Synoptic Patterns during 1990-1993 in the eastern/central North Pacific.

smaller TCs in the eastern/central North Pacific basin. The TC is under the influence of the Low (L) or Multiple (M) TC Patterns in only 3% and 1%, respectively, of the cases in this four-year sample. These are much smaller frequencies than for the western North Pacific (11% and 4%, respectively).

b. Region Frequency

Within each Synoptic Pattern, it is the Synoptic Region (Table 4) that determines the environmental flow experienced by the TC. Three of these Synoptic Regions occur in more than one Synoptic Pattern because similar flows exist within these smaller areas. The Dominant Ridge (DR) Region comprises 73% of all classifications (Fig. 15). The large percentage (only 54% for the western North Pacific) of DR is a direct result of the prevalence of the subtropical ridge poleward of the TCs. The second most common (15%) Synoptic Region is the Weakened Ridge (WR), which is a much larger percentage than occurs in the western North Pacific (4%). In the western North Pacific, storms spent little time in the WR Region as they tend to recurve rapidly in the S/AW or return to the S/DR in a "failed recurvature." However, the effects of SRM in the eastern/central North Pacific tend to cause TCs to transition into or out of the WR Region much more easily and more often. Only 4% of the cases are in the Weak Westerly (WW) Synoptic Region. This Region, which is poleward of the subtropical ridge and characterized with westerlies of moderate strength (Fig. 13), is where TCs of the eastern/central North Pacific commonly dissipate.

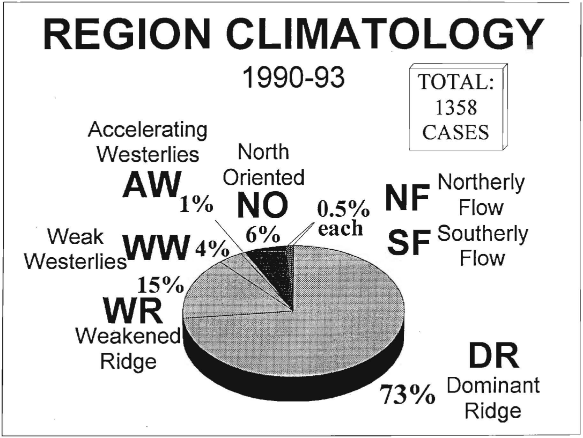


Figure 15. Percentage of the 1358 characterizations of the Synoptic Regions during 1990-1993 in the eastern/central North Pacific.

Although present in two Synoptic Patterns, the North-Oriented (NO) Synoptic Region only comprises 6% of the 1358 cases, which is considerably reduced from the 24% of the cases in the western North Pacific. The smaller number of NO Region characterizations in the eastern/central North Pacific is tied to the smaller frequencies of the N and L Patterns (or G Pattern in the western North Pacific).

Even though the Accelerating Westerlies (AW) Region exists in three (hypothetical in the L) Synoptic Patterns (Table 4), it only constitutes 1% of the eastern/central North Pacific cases, which is considerably less than the 14% of the cases in the western North Pacific. This small frequency is attributed to the dissipation of eastern/central North Pacific TCs before reaching the strong westerlies. It is more common (4%) for the eastern/central North Pacific storms to be in the S/WW combination. Finally, the Multiple (M) TC Pattern Northerly Flow (NF) and Southerly Flow (SF) Synoptic Regions each contribute only 0.5% of the cases, and thus are rather rare events.

c. *Pattern/Region Frequency*

Although the flows in the same Synoptic Region of different Synoptic Patterns will be similar, the storm tracks may be slightly different because of the different large-scale environmental forcing. For example, TCs in the N/NO and L/NO Pattern/Region combinations are under the influence of a basically southerly environmental flow. The storm track in the N/NO Pattern/Region may vary from northwestward clockwise to northeastward depending on the tilt of the ridge. The track in the L/NO

Pattern/Region combination will vary from northward counter-clockwise to northwestward due to the presence of the cyclonic circulation in the southwest. Hence, a census of specific Pattern/Region combinations (Fig. 16) is necessary.

The S/DR Pattern/Region combination is the most frequent at 73.2%, which is an increase from the 50.8% frequency for the western North Pacific. Surprisingly, the second most common Pattern/Region combination is the S/WR at 15.2%, since this is a large increase from the 3.9% frequency in the western North Pacific. The third most common Pattern/Region combination is the S/WW at 3.6%. These three Pattern/Region combinations comprise well over 90% of all cases. The predominance of these three Pattern/Region combinations is believed to be related to the strength and prevalence of the subtropical ridge in the eastern/central North Pacific. Another factor is that these TCs tend to dissipate at lower latitudes where the SST values are smaller. Consequently, the eastern/central North Pacific storms form at lower latitudes and do not interact with the midlatitude circulations.

In the N Pattern, all of the cases (3.4% of overall sample) are tracking northward in the NO Region. Although the S/AW combination was observed in 0.7% of the cases, neither the N/AW or the L/AW were observed in this four-year sample. Reasons for the very low (or nill) frequency of occurrence for the eastern/central North Pacific TCs in the environmental flow characteristic of the AW Region were discussed in Section B above. As in the N Pattern, all of the L Pattern cases (2.6%) track northward in the NO Region. Because the L Pattern tends to dissipate within 36-48 h, a smaller

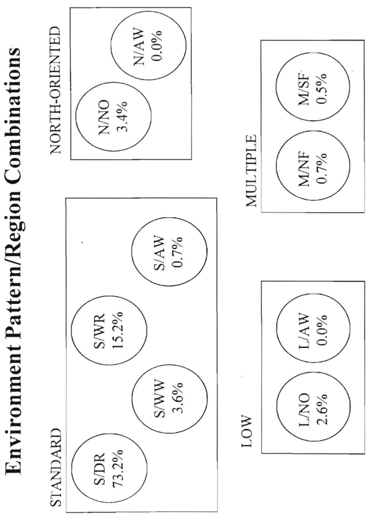


Figure 16. Frequency of Synoptic Pattern/Region combinations in the eastern/central North Pacific during 1990-1993.

frequency of occurrence for the overall L Pattern, as well as the L/AW Pattern/Region combination, is to be expected.

The simple percentages of the overall sample of assignments discussed above do not reflect the differing lengths of time that a TC may spend in the varying Pattern/Region combinations. While some assignments persist for a week, others only last for one 12 h period. The length of time in each Pattern/Region will vary because the horizontal domain of each Pattern/Region varies greatly, the translation speeds through each Pattern/Region differ, the Pattern/Region may only exist as a transitional state, and some Environment Structures are dissipative. Therefore, some Pattern/Region combinations may appear to be under-represented and give a forecaster the wrong impression as to the relative importance of a particular Pattern/Region.

An alternate method for counting the Environment Structures in the four-year sample is to count each Pattern/Region occurrence separately, regardless of how long the TC remains in that Pattern/Region. This method of counting reduces the 1358 date-time groups (DTGs) for the 90 TCs to a total of 176 assignments (Table 5b). Only three Synoptic Pattern/Region combinations have a significant change in their percentages of occurrence with the new counting method. The S/DR combination is reduced from 73.2% (Table 5a) to 58% (Table 5b) of the occurrences because of the long periods that many TCs spend in this Pattern/Region. Over half of the reduction in the S/DR combinations is compensated by an increase in the S/WR combination as it increases from 15.2% (Table 5a) to 26.1% (Table 5b) of the total occurrences. The final significant change is in the

Table 5. (a) Number of the 1358 DTGs the TCs are in the Synoptic Pattern/Region, and (b) number of times (regardless of duration) the 90 TCs are in the Pattern/Region combination.

a

		%
S/DR	995	73
S/WR	207	15
S/WW	49.5	3.6
S/AW	10	0.7
N/NO	46	3.4
L/NO	35	2.6
M/NF	9.5	0.7
M/SF	6.5	0.5
TOTAL	1358	

b

		%
S/DR	102	58
S/WR	46	26
S/WW	9	5.1
S/AW	5	2.8
N/NO	7	4
L/NO	7	4
M/NF		
M/SF		
TOTAL	176	

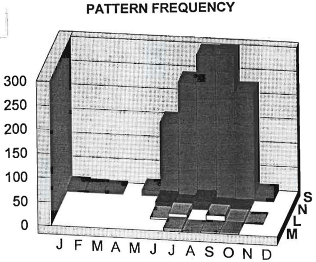
S/AW percentages that increases from 0.7% (Table 5a) to 2.8% (Table 5b), because of the short amount of time TCs remain is this Synoptic Pattern/Region before dissipating. The absence of any DTGs for both the M/NF and M/SF is reflected in the absence of either of these Pattern/Region combinations being considered the sole Environment Structure for the TCs, Section E of this Chapter. While the percentage for occurrences of the Pattern/Region combinations do change, none of the percentages changes have a significant impact on the prior frequency estimates.

d. Seasonal Variations

As the large-scale environment changes with the seasons, the Environment Structure changes seasonally (Fig. 17). In this four-year sample, TCs were observed in every month except April and December. Although the S Pattern has the highest occurrence percentage in each month, this is particularly prominent in the months of May through October, because of the increased number of TCs in the eastern/central North Pacific that are found equatorward of the persistent subtropical ridge.

The shallow bell-shaped curve for the L Pattern with the complete lack of this Pattern/Region for August is curious, but may just be an artifact of this four-year sample set. The early- and late-season maxima in the frequency of the L Pattern are consistent with its formation from an upper-level low developing downward to the surface at those times of the season when cutoff Lows are observed in the tropics.

a



b

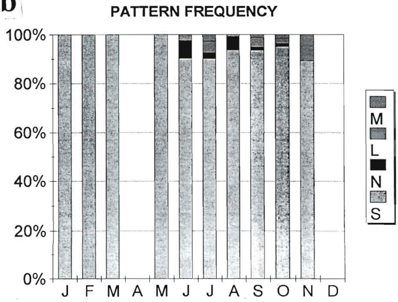


Figure 17. Monthly (a) occurrences and (b) percent frequency of the Synoptic Patterns in eastern/central North Pacific TCs during 1990-1993.

2. Synoptic Pattern/Region Tracks

The importance of assigning accurately the Environment Structure is illustrated by summaries of TC tracks in each Pattern/Region combination. Summaries of TC tracks in each Pattern/Region are shown in Figs. 18-20. The tracks in the S/DR Pattern are generally as expected (Fig. 18a). Tracks associated with the S/DR Pattern/Region are basically long, east-west tracks south of 30°N, and are expected to increase in latitude as the TC proceeds to the west due to Beta-Effect Propagation (BEP), see CE. The tracks of TCs in the eastern subtropical ridge subregion (Fig. 18b) are northwestward due to the northwestward environmental steering and BEP, see Section E for description of the S/DR subregions. The tracks of TCs in the western subregion (Fig. 18c) are generally west-northwestward to west-southwestward. Even though the large-scale environmental steering is generally southwestward, TCs of sufficient size (see CE) are able to alter (via the BEP TC-Environment Transformation) the environmental steering in their immediate vicinity such that several storm tracks are predominantly westward.

The S/WR tracks (Fig. 19a) are typically short as TCs that move through the subtropical ridge generally dissipate quickly in the eastern/central North Pacific. These S/WR tracks are mostly to the northwest to northeast as a TC is moving through the subtropical ridge, although some move toward the southeast to southwest direction as the TCs are being forced back into the ridge. As expected, tracks associated with the S/WW Pattern/Region are northeastward (Fig. 19b) because TCs in this Pattern/Region are located on the north side of the subtropical ridge. The S/AW tracks (Fig. 19c) are all

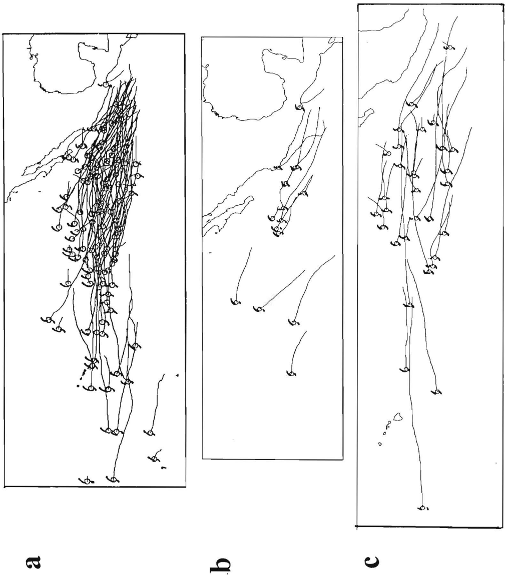
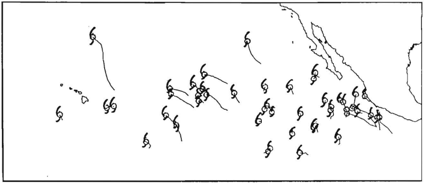


Figure 18. Storm tracks during 1990-1993 while the storm is in the Standard Pattern and the (a) Dominant Ridge, (b) eastern subregion of the Dominant Ridge, and (c) western subregion of the Dominant Ridge Region.

a



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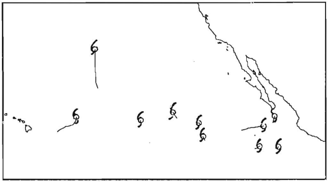

c

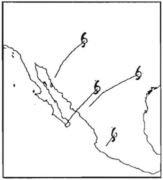

Figure 19. Storm tracks as in Fig. 18, except in the Standard Pattern and the (a) Weakened Ridge, (b) Weak Westerlies, and (c) Accelerating Westerlies Regions.

landfalling storms that do not possess the characteristic west-east elongated tracks found in the western North Pacific. The persistence of the subtropical ridge located over the mountainous Central Americas effectively produces northeastward tracks for the S/AW combination.

The tracks of the N/NO (Fig. 20a) Pattern/Region combination are northwestward through northeastward due to the generally north-south orientation of the subtropical ridge, which is most commonly affected by the SRM transitional mechanism associated with the mid-latitude troughs and ridges. The tracks of the L/NO (Fig. 20b) Pattern/Region combination are also associated with northwestward to northeastward motion. The track of Iniki (long northward track west of Hawaii) shows the combined steering effect of the cyclonic circulation of the L Pattern as it translates northward along with the NO Region on the eastern side of this cyclonic circulation.

The tracks of TCs identified as being influenced by vertical wind shear (VWS) are provided in Fig. 21a. The effect of VWS is evident in those tracks that are northwestward before and southwestward after the TC-Environment Transformation of VWS, or those continuous northwestward tracks that dissipate. For example, TC Carlos is tracking northwestward in response to an environmental flow pattern that represents a transitional state between S/DR to N/NO Pattern/Region combinations (Fig. 22). On 0901 UTC 25 June 1991, the separation of the convective cloud mass (CCM) and the low-level circulation (LLC) of TC Carlos is evident in Fig. 23. As a result, the track of Carlos (Fig. 21a, dashed track) becomes more westward as the effective steering level is lowered to

a

b

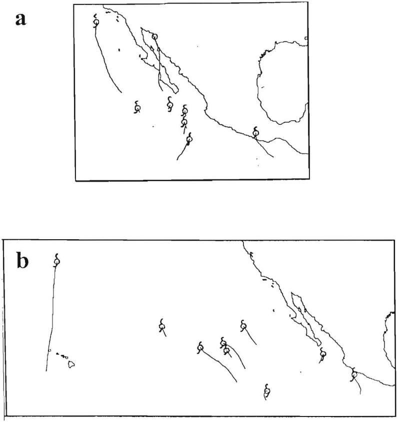

Figure 20. Storm tracks as in Fig. 18, except in the North-Oriented Region within the (a) North-oriented and (b) Low Synoptic Patterns.

a

b

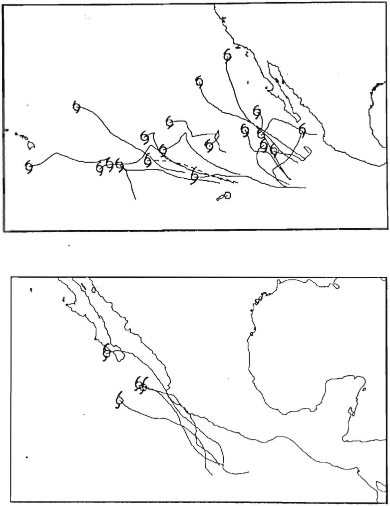

Figure 21. Storm tracks during 1990-1993 while the storm is in the transformation mechanism characterized by (a) vertical wind shear +/- two days of occurence (TC Carlos is the dashed track), and (b) the orographic effect.

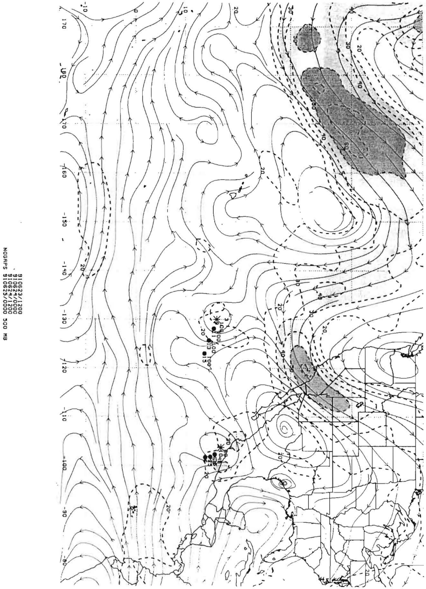

Figure 22. NOGAPS 500 mb streamline and isotach analysis for Hurricane Carlos at 0000 UTC 25 June 1991. Hurricane Carlos is TC3 in the center of the domain.

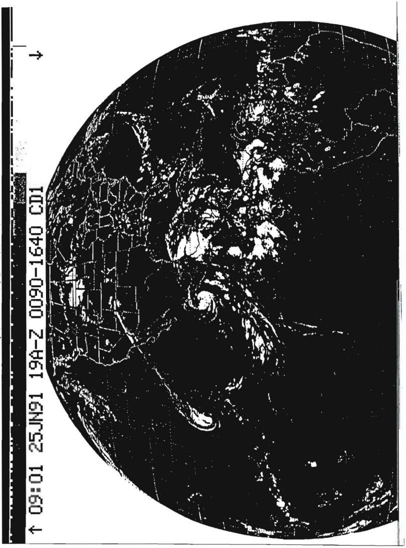

Figure 23. Geostationary infrared image of Hurricane Carlos at 0901 UTC 25 June 1991.

700 mb streamline. That is, TC Carlos' track is no longer associated with environmental steering reflected by the 500 mb NOGAPS streamline analyses. On the other hand, the TC tracks that proceed northwestward through northeastward while under the influence of VWS are dissipating over the colder waters found in the higher latitudes of the eastern/central North Pacific region.

As described in Section E, the tracks associated with orographic effect (Fig. 21b) characteristically reveal a northward motion along and toward the western side of the Sierra Madre of Mexico. These track orientations occur despite the northwestward environmental steering associated with the eastern subregion of the S/DR Pattern/Region combination.

3. Synoptic Pattern/Region Transitions

The utility in classifying the Environment Structures in the eastern/central North Pacific into recurring Pattern/Region combinations is that characteristic tracks may be associated with each Pattern/Region combination. The tracks of storms within each of the Synoptic Pattern/Region combinations are expected to persist until an Environment Structure transition occurs. Thus, these transitions are critical to the forecaster's ability to anticipate the Environment Structure Transformations and to forecast accurately the TC track changes.

A "complete" transition is defined as when an actual change of either Synoptic Pattern, Synoptic Region, or both occurs. This is the only type considered for this discussion. The Environment Structure can change as the result of: (i) TC-Environment transformations (Fig. 3); and/or (ii) changes in Environment Structure that do not principally depend on the presence of a TC (Fig. 4). The TC-Environment transformations (Fig. 24) and the Environment effects (Fig. 25) are the Transitional Mechanisms that are identified for this four-year sample of eastern/central North Pacific TCs.

Based on this four-year sample of the eastern/central North Pacific, each Environment Structure transition (Fig. 26) is associated with one or more of the transitional mechanisms that are shown in Figs. 24 and 25. In the western North Pacific sample, 248 transitions occurred with 30 different types of transitions (Carr et al. 1995). In comparison, the eastern/central North Pacific four-year sample only has 77 transitions and only 11 different transitions among the Pattern/Region combinations. The number of transitions entering a Pattern/Region does not have to equal the number exiting the Pattern/Region because TCs can develop or dissipate within any of the Pattern/Region combinations. The small number of transitions for the eastern/central North Pacific is understandable since these TCs tend to dissipate before they reach the mid-latitudes, thus precluding transitions associated with recurvature.

The numbers in Table 4 indicate there are 176 Pattern/Region occurrences for the 90 TCs in the four-year sample, so that the average TC would seem to undergo two transitions in their lifetime. However, 30 (39.0%) of the sample TCs undergo no transitions (numbers within the Pattern/Region circles in Fig. 26) of which 29 remained in the S/DR combination during their entire lifetime. After subtracting the 30 TCs without a

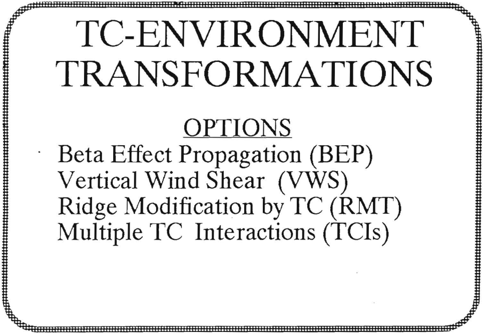

Figure 24. As in Fig. 3, except TC-Environment transformations for the eastern/central North Pacific.

ENVIRONMENT EFFECTS

<u>OPTIONS</u>

Advection by Environment (ADV)
Mid-level Low Formation (MLF)
Mid-level Low Dissipation (MLD)
Subtropical Ridge Modulation (SRM)

Figure 25. As in Fig. 4, except Environment Effects for the eastern/central North Pacific.

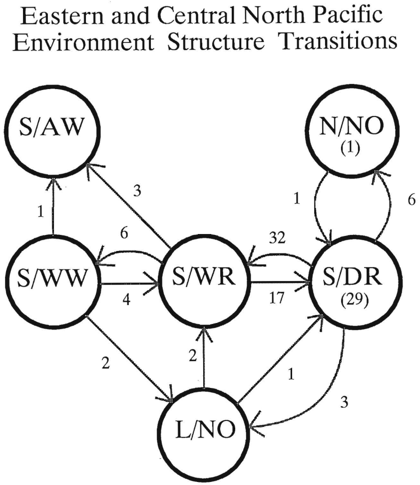

Figure 26. All transitions between Synoptic Pattern/Regions for the four-year sample. The numbers represent how many times the transition occurred. Numbers within each circle indicates storms that remained in that Pattern/Region throughout the life cycle.

transition, the 60 TCs that do undergo a transition have an average of three transitions during their lifetimes. Because of the small number of all transitions, even the single transitions are included in Fig. 26 because the potential importance to forecasting TC track changes.

Surprisingly, the Pattern/Region most commonly involved in transitions is the S/WR combination, even though 207 (15.2%) of the cases are identified as S/WR in the four-year sample (Table 4). A large fraction of the 77 transitions, i.e., 32 (41.5%) for the S/DR to S/WR and 17 (22.1%) for the S/WR to S/DR, reflects the persistence of the subtropical ridge. In addition, the reduced (relative to western North Pacific) effect of RMT (owing to smaller TC size) as the TC propagates northwestward into the weaker portions of the subtropical ridge, and the effects of SRM after the TC reaches its maximum poleward extent, also contribute to these two dominant transitions. The persistence of TCs in the S Pattern is reflected by the 6 (8%) and 3 (4%) transitions into the S/WW and S/AW, respectively. The total number of transitions into the S/WR (38, or 49.3%) results from the dissipation of many of the TCs in the eastern/central North Pacific while in the S/WR combination.

The S/WW Pattern/Region had 49.5 (3.6%) occurrences (see Table 4) and was involved in 13 transitions (Fig. 26). Although six transitions into S/WW are via the expected route of S/WR, four returned back to the S/WR. Only one transition follows the typical western North Pacific continuation to S/AW. Four of the six TCs that transition into the S/WW dissipated.

The N/NO Pattern/Region combination was involved in seven (9%) of the 77 transitions. All of these transitions involved the S/DR Pattern/Region, including one return transition to the S/DR combination. Of the six transitions into the N/NO, two were observed to dissipate due to the northward motion of these TCs over colder waters. Thus, the N/AW Pattern/Region was not identified in this four-year sample.

The L/NO Pattern/Region is involved in only five of the 77 transitions identified for this four-year sample, which may be a consequence of the four-year sample. Interestingly, two transitions into the L/NO Pattern/Region are from the S/WW Pattern/Region. Nevertheless, none of the complete transitions into the L/NO Pattern/Region persisted for longer than 48 h duration before transitioning back into one of two Regions of the S Pattern. This reflects the short-life span of the L Pattern as described in Section F above. As is the case for the N/AW Pattern/Region, the L/AW Pattern/Region is not observed in this sample due to the dissipation of TCs as they propagate over colder waters and the dissipative nature of the L Pattern.

IV. CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

Carr and Elsberry (1994) hypothesized that the meteorological framework of the Systematic Approach would be generally applicable to other tropical basins of the world. The intention of characterizing the large- and medium-scale synoptic features near tropical cyclones (TCs), as represented in an operational analysis, is to apply the meteorological knowledge base for TC track forecasting, which includes anticipating the temporal and spatial changes to be expected in these synoptic features. An updated knowledge base (Carr et al. 1995) developed from a five-year investigation of western North Pacific TCs was utilized as a starting point. A similar investigation here of all eastern and central North Pacific TCs from 1990-1993 resulted in some modifications and variations in the Environment Structure and TC-Environment transitional mechanisms compared to those of Carr and Elsberry (1994) and Carr et al. (1995). In addition to not finding any monsoon Gyre (G) Patterns, an entirely new Low (L) Synoptic Pattern was developed to represent a recurring Environment Structure in the eastern/central North Pacific. A new Weak Westerly (WW) Synoptic Region in the Standard (S) Pattern was also defined to better represent the structure of the subtropical ridge and its effect during the post-recurvature phase of the eastern/central North Pacific TCs.

This four-year (1990-1993) sample of eastern and central North Pacific TCs was used to calculate the Synoptic Pattern, Region, and Pattern/Region frequencies and a preliminary Environment Structure transition climatology. The S Pattern is the most prevalent (92.7%) Pattern because of the dominance of the subtropical ridge in eastern and central North Pacific TC motion. The North-oriented (N), Low (L), and Multiple (M) TC Patterns with 3.4%, 2.6%, and 1.2%, respectively, are relatively uncommon in this data sample. The Dominant Ridge (DR) Region is by far the most common (73.2%) Synoptic Region in the eastern/central North Pacific, due to the long TC tracks equatorward of the subtropical ridge. Whereas the preponderance of the S Synoptic Pattern and this Synoptic Region emphasize the persistence of the mid-tropospheric subtropical ridge, two subregions with different tilts lead to varying steering flows and TC tracks presumably depending on TC size and associated β-effect propagation (BEP). The next most common (15.2%) Synoptic Region is the Weakened Ridge (WR) Region, due to the increased effects of the Environment Structure transformation identified as SRM relative to the frequency (4%) observed in the western North Pacific. Since the N, L, and M Synoptic Patterns are relatively rare, the North-Oriented, Northerly Flow, and Southerly Flow Synoptic Regions also have low frequencies of occurrence. Some distinct seasonality in the Pattern frequencies is noted, with L and M Patterns only occurring in the mid- to late-season.

The summary of transition frequencies for the four-year sample demonstrated that the Pattern/Region most often (83.1%) involved in transitions is the S/WR combination. The importance of the SRM Environment Structure transformation in effecting Pattern/Region transitions, particularly within the S Pattern, is highlighted in this 1990-

1993 sample set. Although the number of TC-Environment Structure transitions is small, the SRM transition that involves mid-latitude trough/ridge systems emphasizes that the TC must get to a relatively high latitude if a transition is to occur. Even though the eastern/central North Pacific has similar transitional mechanisms as in the western North Pacific (see CE), the strength of the subtropical ridge and smaller size of TCs results in the SRM transtional mechanism being more influential in the eastern/central North Pacific compared to the western North Pacific.

In conclusion, the Systematic Approach with some modifications is determined to be very applicable to the eastern/central North Pacific. The association of TC tracks with Synoptic Pattern/Region combinations and the highlighted transitional mechanisms in the eastern/central North Pacific can assist forecasters in better forecasting TC movement via: (i) prompt and consistent recognition of recurring environmental patterns in evolving global model fields; and (ii) association of characteristic TC forecast tracks with those patterns. This knowledge combined with an understanding of the forecast traits of the global numerical model and other objective track forecast aids that depend on the numerical model in similar situations will allow the forecaster to improve upon the objective guidance. While this tool will not guarantee a correct forecast, the Systematic Approach should enhance forecasters abitilies to forecast sudden TC track changes.

B. RECOMMENDATIONS

Although the four-year sample demonstrates the applicability of the Systematic Approach to the eastern/central North Pacific, additional years are needed. Since the four years contained only a total of 90 eastern/central North Pacific TCs, the frequencies of occurrences and the probabilities of transitions must be regarded as only a preliminary climatology. The addition of more years is desirable to obtain more representative frequencies of the Patterns, Regions, Pattern/Region combinations, and transitions.

The dissipation of many TCs in the eastern/central North Pacific as they progressed over the colder waters is markedly different from that observed in the western North Pacific. A study of the influence of the ocean temperatures and other factors such as vertical wind shear associated with the dissipation of these TCs is needed to understand and forecast both the intensity and the tracks of eastern and central North Pacific tropical cyclones.

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